Maximizing the Bandwidth from Supercontinuum Generation in Photonic Crystal Chalcogenide Fibers

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based on the PhD dissertation of:

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now at Princeton University

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Maximizing the Bandwidth from Supercontinuum Generation in Photonic Crystal Chalcogenide Fibers

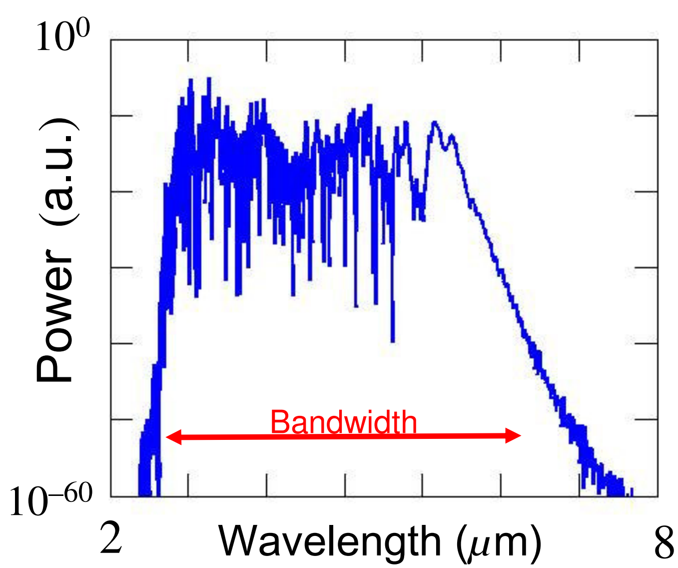
With:

Dr. L. Brandon Shaw, J. S. Sanghera, and I. D. Aggarwal

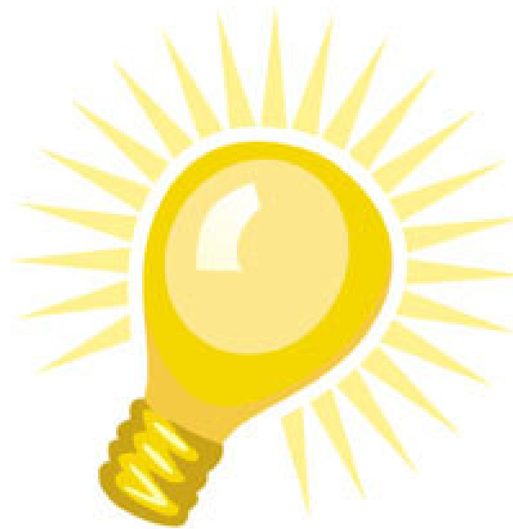
at the Naval Research Laboratory

Project Goal

GOAL: *To make a broadband (2 – 10 μm) mid-IR source*



A mid-IR Light bulb



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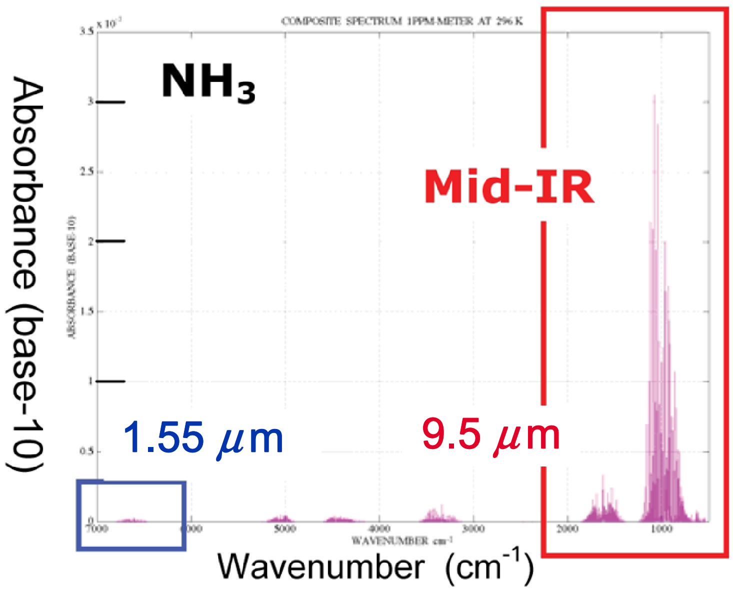
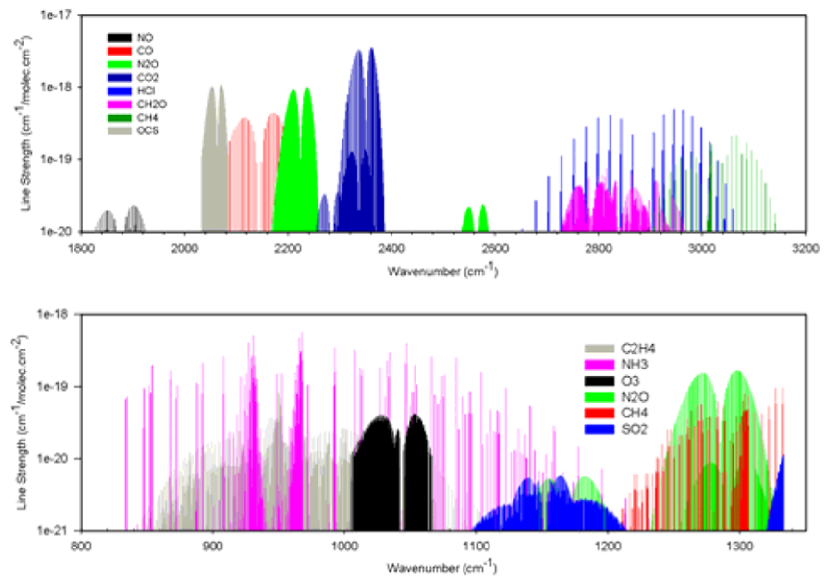
Why mid-IR sources?

Many important materials radiate or absorb in this range

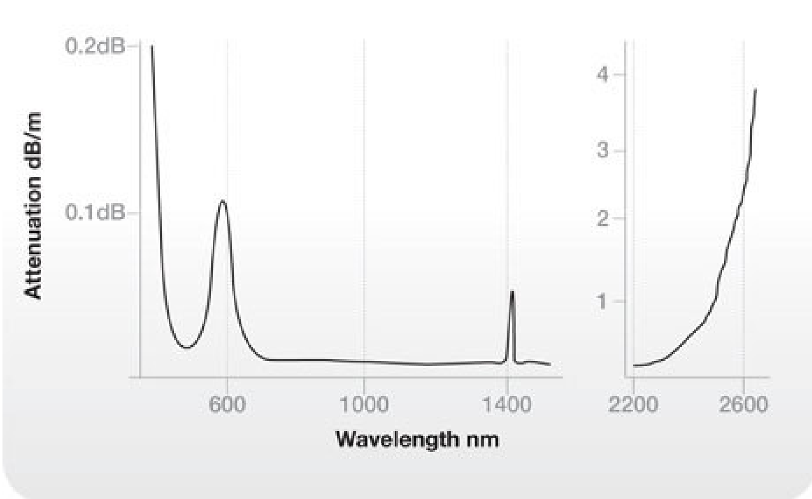




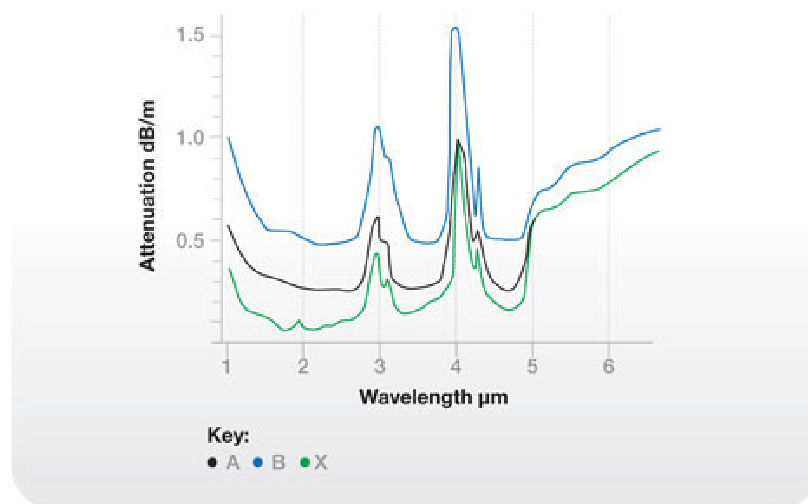
Spectral response of ammonia

…And it is not alone!

Why chalcogenide?



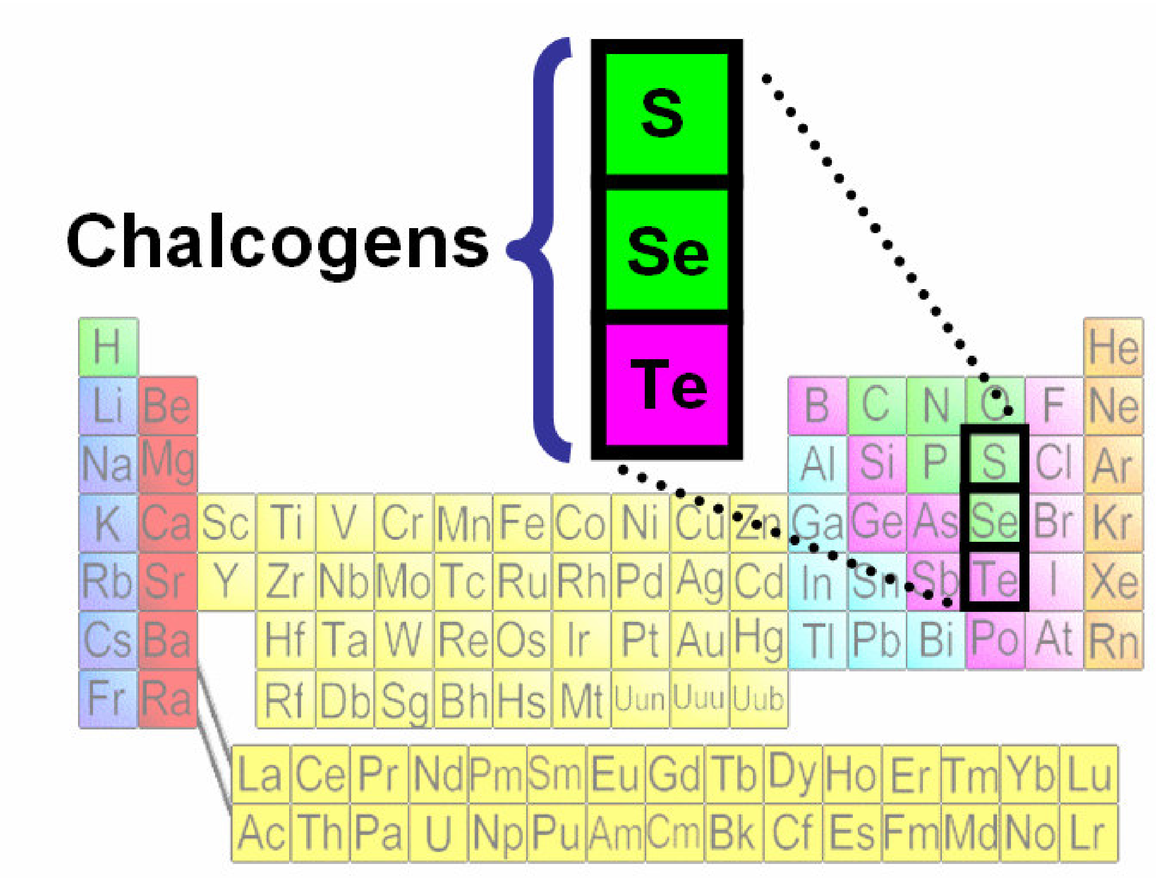
Attenuation in silica grows rapidly beyond 2.5 μm



Attenuation in the chalcogenides remains small beyond 10 μm

Source: Oxford Electronics
www.oxford-electronics.com

What is chalcogenide?



- glass is based on chalcogens mixed with As
- losses ~ 0.1 – 1 dB/m
- Kerr nonlinearity = 1000X silica fiber
- CW peak power = 50 – 125 kW/cm^2
- pulse peak power = 1 – 2 GW/cm^2

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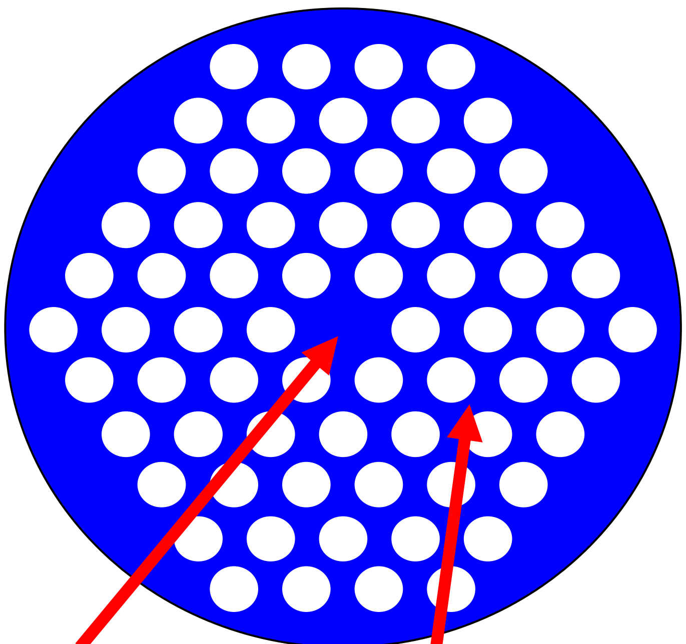
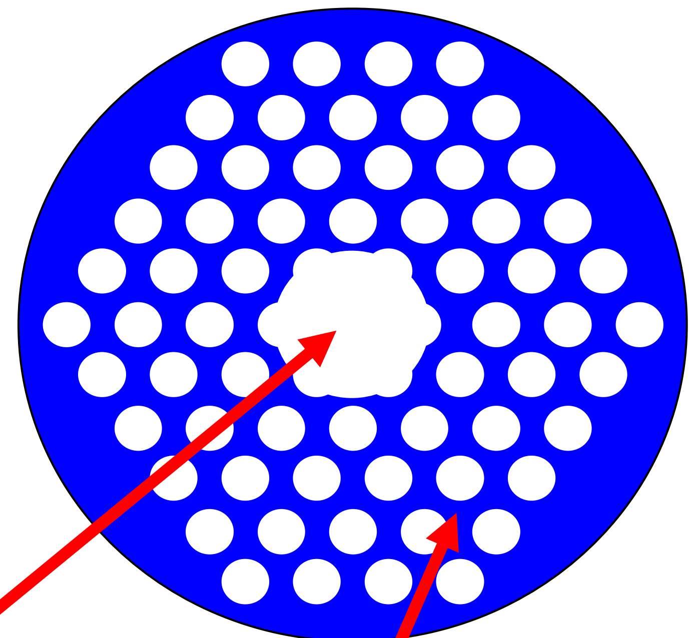
Photonic crystal fiber (PCF)

Solid-core PCF

Photonic bandgap fiber (PBGF)





solid core

holey cladding forms
effective low-index material

Air core

periodic cladding forms
photonic band gap

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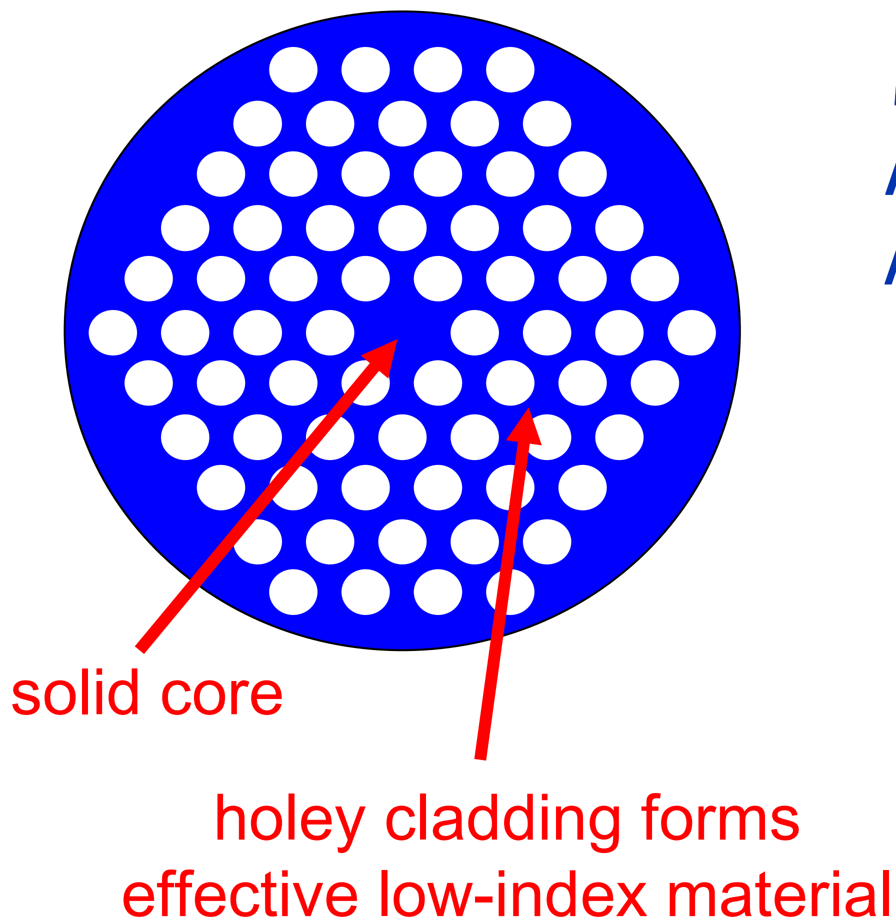
Photonic crystal fiber (PCF)

Solid-core PCF



We focus on solid-core PCFs to make use of the nonlinearity

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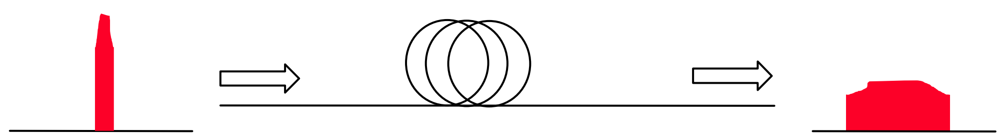
Supercontinuum generation

- Supercontinuum generation
  - ✓Kerr nonlinearity
  - ✓Raman effect
  - ✓Dispersion



It is a complicated, incoherent process!

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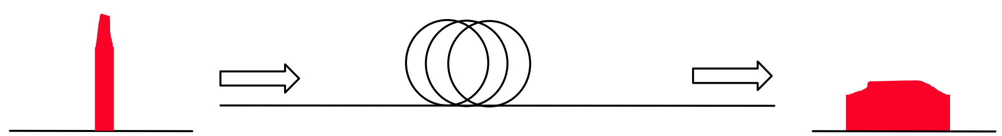
Supercontinuum generation

• Supercontinuum generation
  ✓Kerr nonlinearity
  ✓Raman effect
  ✓Dispersion



• Supercontinuum generation using photonic crystal fiber (PCF)[1]
  ✓Wide single-mode region
  ✓Enhanced nonlinearity
  ✓Tailored dispersion

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[1]Dudley, *et al.,* Rev. Mod. Phys. **78,** 1135 (2006).

Supercontinuum generation

Supercontinuum generation in chalcogenide fibers is not the same as in silica fibers!

WHY?

- Different material properties
- There are no good sources beyond 2.5 – 3.0 μm

Our design goal is to increase the maximum wavelength of the spectrum as rapidly as possible!

[1]Dudley, *et al.,* Rev. Mod. Phys. **78,** 1135 (2006).

Supercontinuum generation

Supercontinuum generation in chalcogenide fibers is not the same as in silica fibers!

A key finding:

supercontinuum generation proceeds in two stages

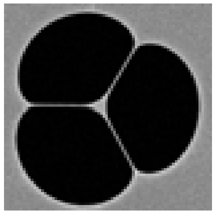
- Stage 1: four-wave mixing
- Stage 2: soliton self-frequency shift

Each stage should be as large as possible!

[1]Dudley, *et al.,* Rev. Mod. Phys. **78,** 1135 (2006).

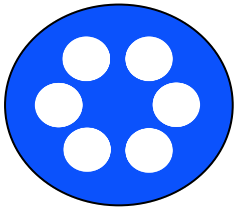
Prior work

- Delmonte, *et al.*[1] show experimental supercontinuum generation from 0.9 to 2.5 μm using a tellurite fiber with a wagon-wheel structure.



- Price, *et al.*[2] theoretically demonstrate supercontinuum generation from 2 to 4 μm using a bismuth glass fiber with a wagon-wheel structure.

- Shaw, *et al.*[3] show experimental supercontinuum generation from 2.1 to 3.2 μm in a As_2Se_3 based chalcogenide PCF with one ring of air holes.



[1]Delmonte, *et al.,* CLEO, CTuA4 (2006)
[2]Price, *et al.,* J. Sel. Topics Quantum Electron. **13,** 738 (2007).
[3]Shaw, *et al.*, Adv. Solid State Photonics TuC5 (2005)

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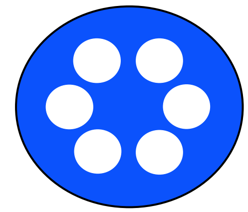
Model validation

- Shaw, *et al.*[1] show experimental supercontinuum generation from 2.1 to 3.2 μm in a As_2Se_3 based chalcogenide PCF with one ring of air holes.



We use the Shaw, et al. results to validate our model

[1]Shaw, *et al.*, Adv. Solid State Photonics, TuC5 (2005).

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Design criteria

Supercontinuum generation is a complicated process

BUT

there are general design criteria that work well

1. Design the fiber so that it is single-mode
   — increases the effective nonlinearity
2. Ensure that four-wave mixing is phase-matched with the largest possible Stokes wavelength
   — Rapidly moves energy to a large wavelength
3. Make the second zero dispersion wavelength as large as possible
   — Allows the soliton self-frequency shift to go to long wavelengths

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A specific example

Fixed fiber and pulse features

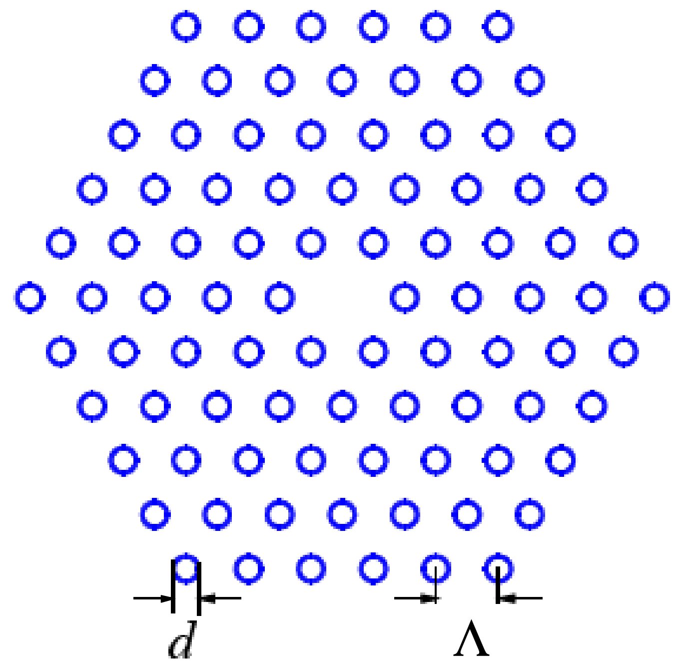
- As_2Se_3 fiber
- Five-ring hexagonal structure
- A pump wavelength of 2.5 μm

Fiber parameters to vary:

- Air-hold diameter (d)
- Pitch (Λ)

Pulse parameters to vary:

- Peak power
- Pulse duration



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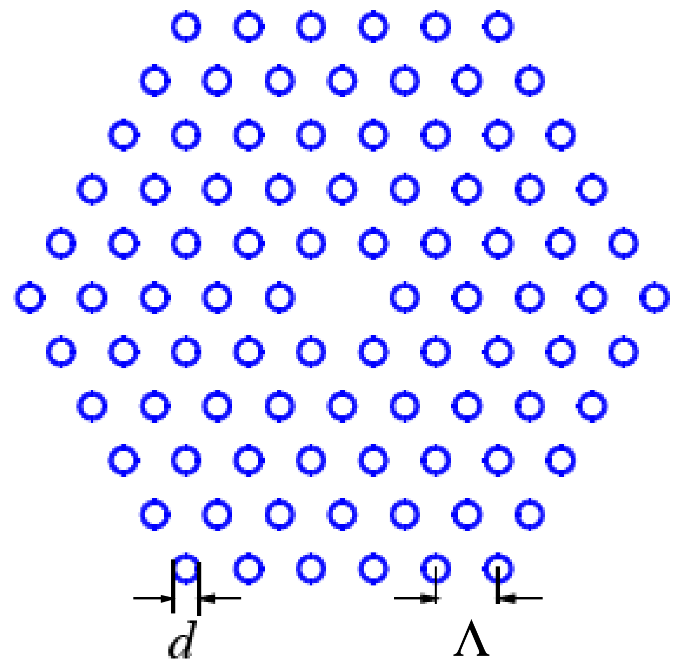
A specific example

Needed fiber quantities
(experimentally determined)

- Kerr coefficient
- Raman gain
- Material dispersion

Needed fiber quantities (calculated)

- Total Raman response
  - calculated once
- Total dispersion
  - calculated for each set of fiber parameters



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Generalized nonlinear Schrödinger equation (GNLS)

In principle: We can optimize by solving the GNLS for a broad set of fiber and pulse parameters

$$\frac{\partial A(z,t)}{\partial z} - i\mathrm{IFT}\left\{\left[\beta(\omega_0+\Omega)-\beta(\omega_0)-\Omega\beta'(\omega_0)\right]\tilde{A}(z,\Omega)\right\}$$

$$= i\gamma\left(1+\frac{i}{\omega_0}\frac{\partial}{\partial t}\right)\left[A(z,t)\int_{-\infty}^{t}R(t')\left|A(z,t-t')\right|^2 dt'\right]$$

$A(z,t)$: Electric field envelope

β : Propagation constant

$\gamma = n_2\omega_0/(cA_{\mathrm{eff}})$: Kerr coefficient

$$R(t) = \underbrace{(1-f_R)\delta(t)}_{\text{Kerr effect}} + \underbrace{f_R h_R(t)}_{\text{Raman effect}}$$

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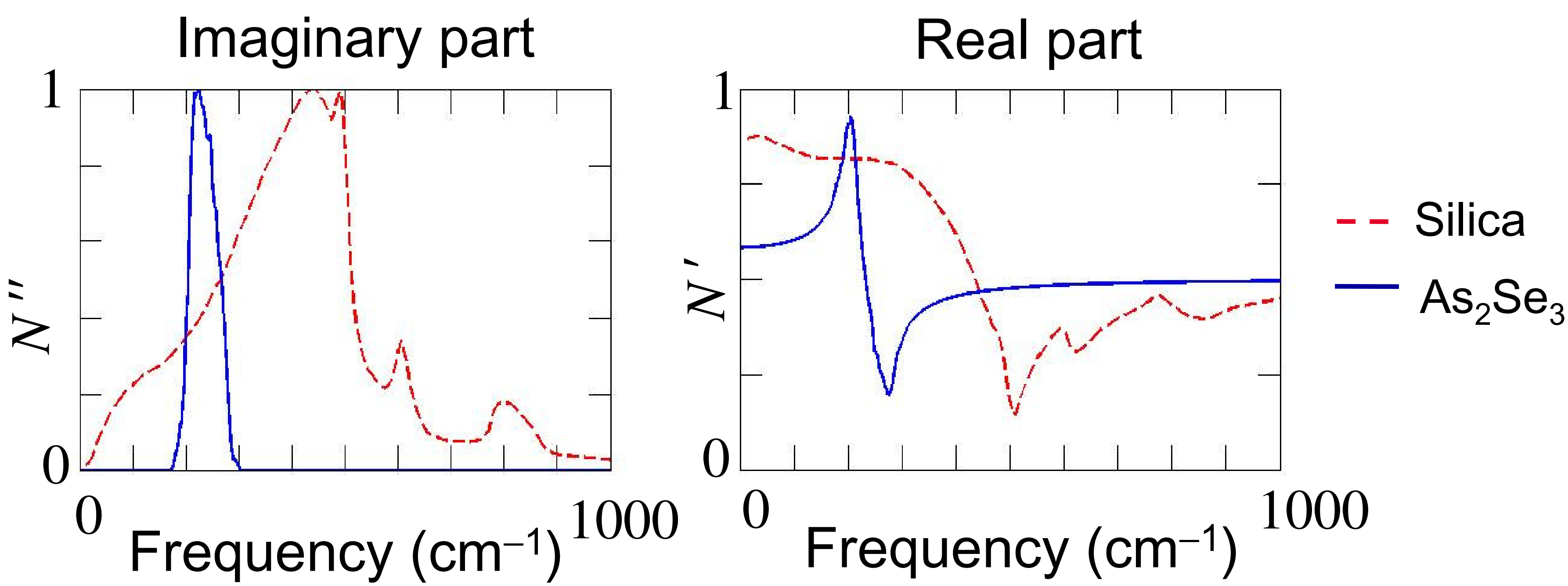
Generalized nonlinear Schrödinger equation (GNLS)

In practice: We use our design criteria to reduce the labor

In any case: We must solve the GNLS for a broad enough parameter set to verify the design criteria

Third-order susceptibility



The real part is obtained by a Hilbert transform of the imaginary part (Kramers-Kronig relation)

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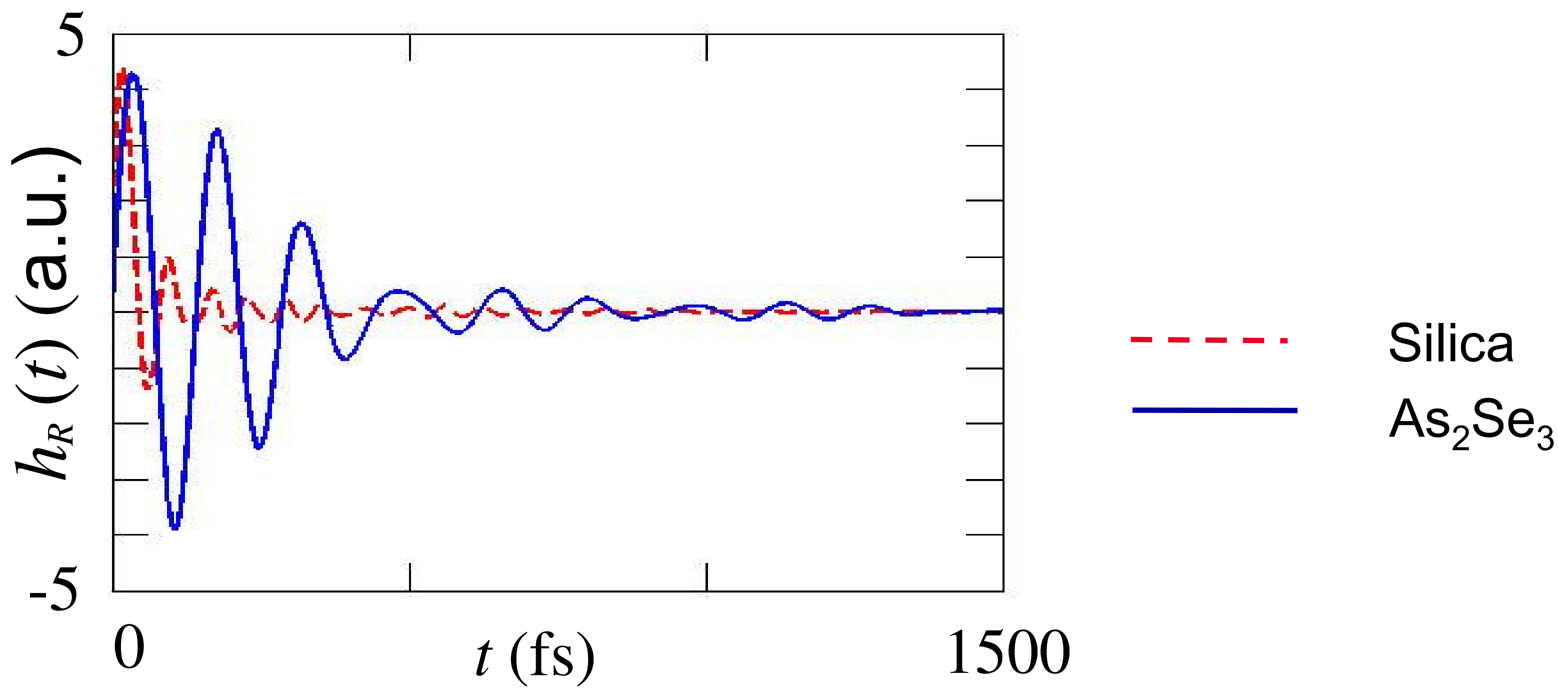
Raman response function



Chalcogenide fiber has a longer response time than silica fiber

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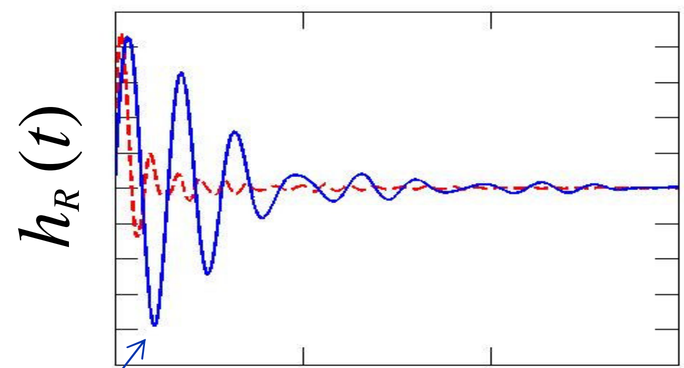
Raman gain and Raman response function

$$R(t) = \underbrace{(1 - f_R)\delta(t)}_{\text{Kerr effect}} + \underbrace{f_R h_R(t)}_{\text{Raman effect}}$$



$$g(\Omega) = (2\omega_p / c) n_2 f_R \,\mathrm{Im}\left[\mathrm{FFT}(h_R(t))\right] \Longrightarrow f_R \approx 0.1$$

Raman gain

Pump frequency

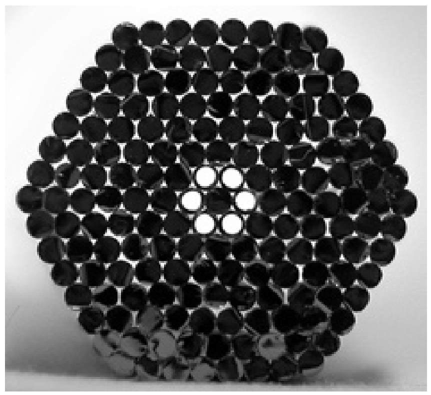
Raman fraction of the nonlinearity

[1]Stolen, *et al.*, J. Opt. Soc. Am. B **6**, 1159 (1989).

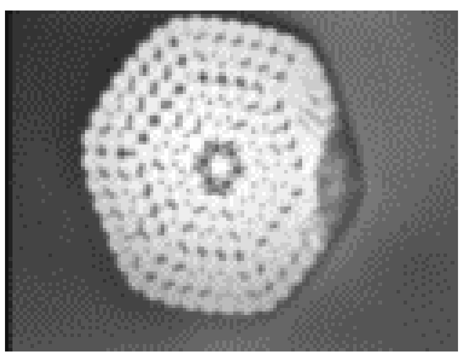
[2]Slusher, *et al.*, J. Opt. Soc. Am. B **21**, 1146 (2004).

Fiber geometry

Experiment[1]

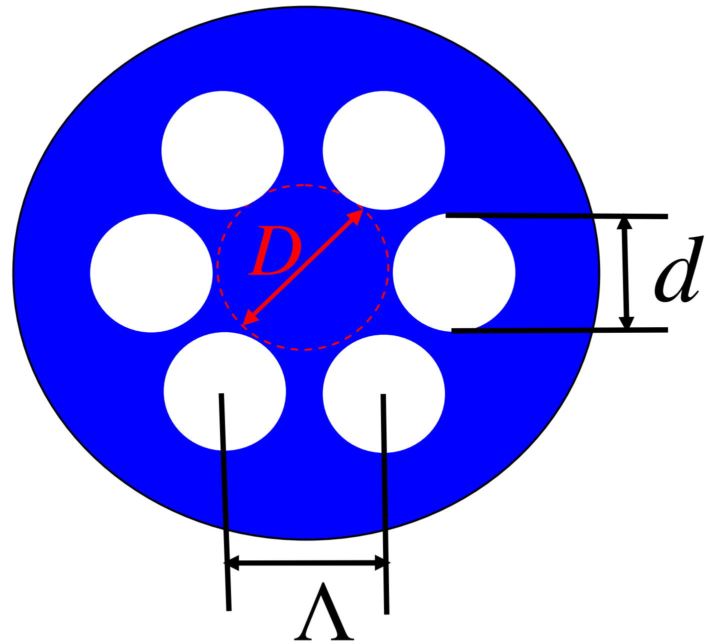


Preform



PCF

Simulation



$D = 10\ \mu\text{m}$
$d/\Lambda = 0.8$

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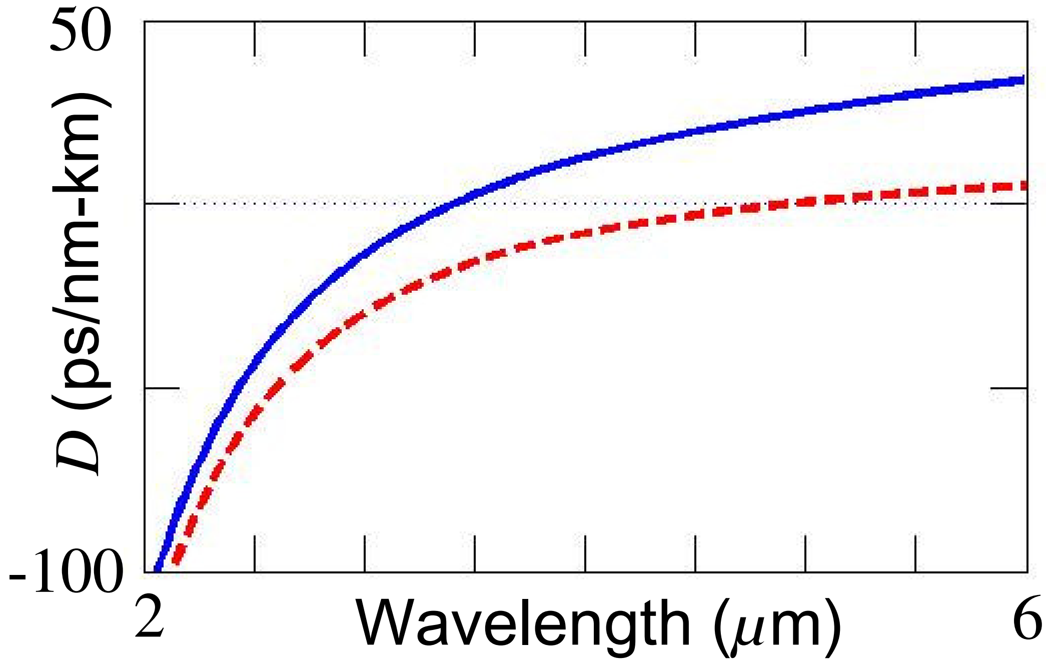
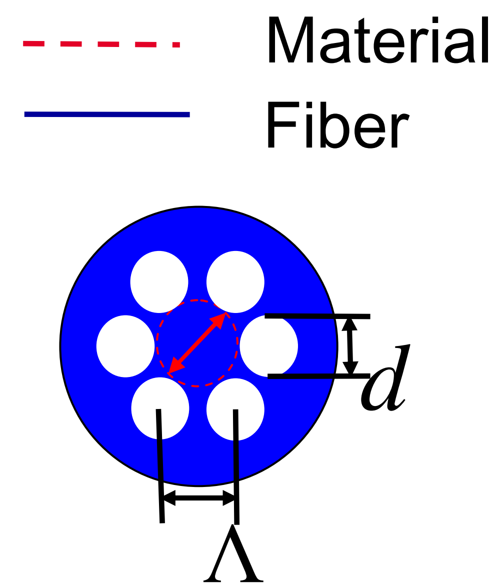
[1]Shaw, *et al.*, Adv. Solid State Photonics, TuC5 (2005)

Dispersion





$D = 10\ \mu$m

$d/\Lambda = 0.8$

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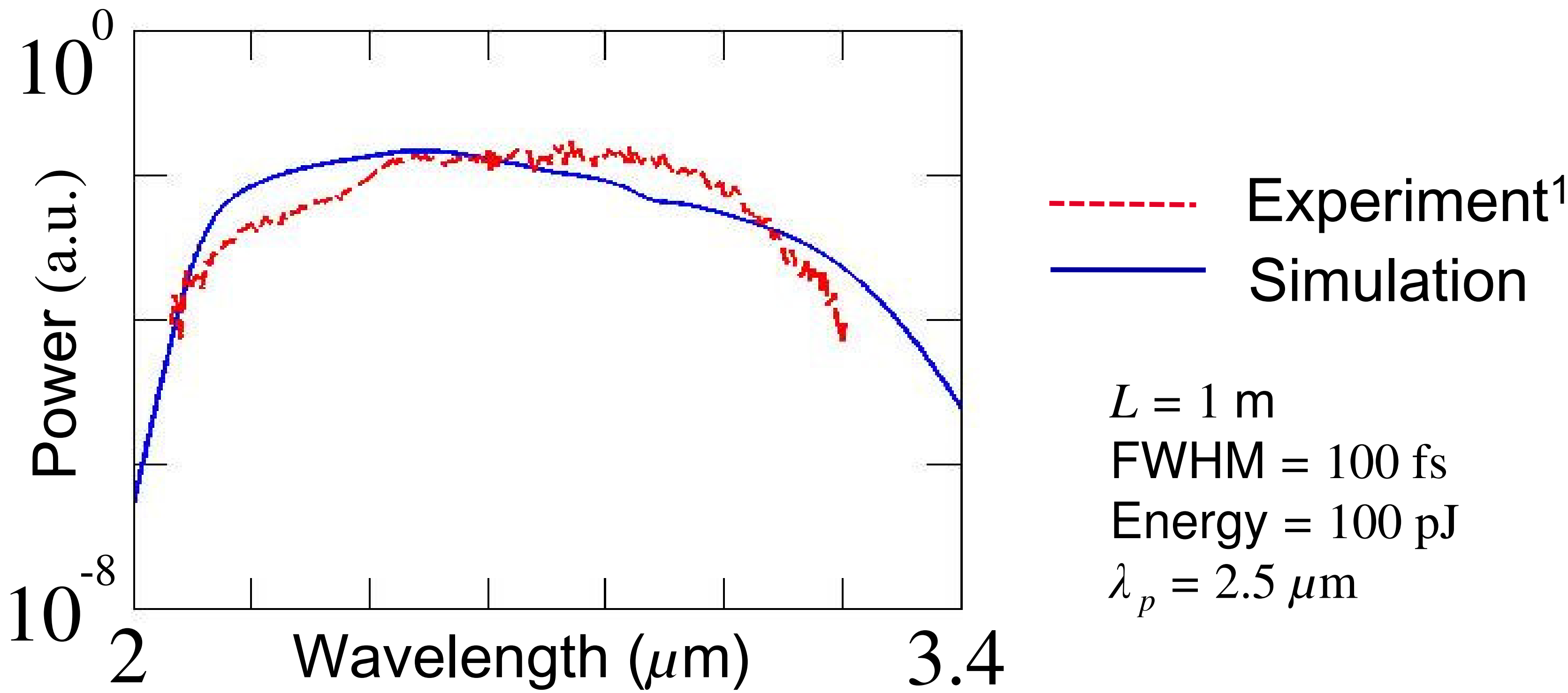
Supercontinuum generation



L = 1 m
FWHM = 100 fs
Energy = 100 pJ
λ_p = 2.5 μm

Measured nonlinear response can completely account for the supercontinuum generation

[1]Shaw, *et al.*, Adv. Solid State Photonics, TuC5 (2005)

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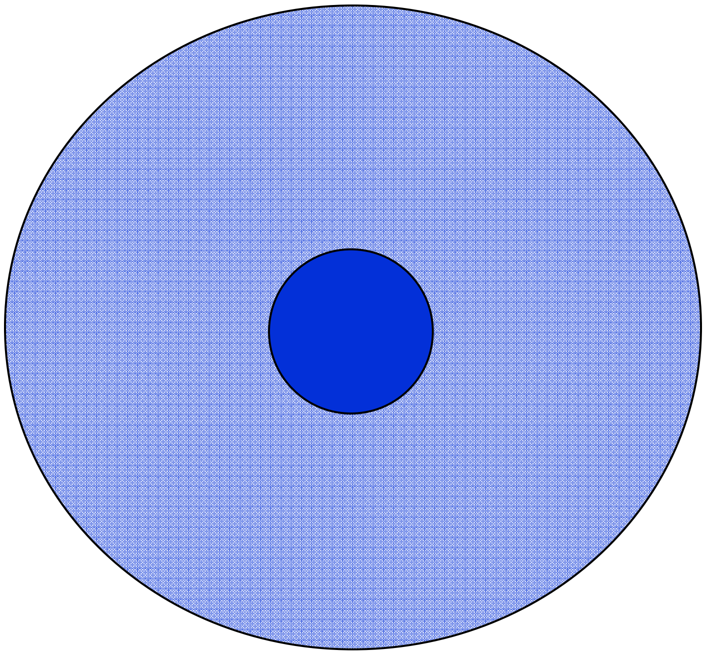
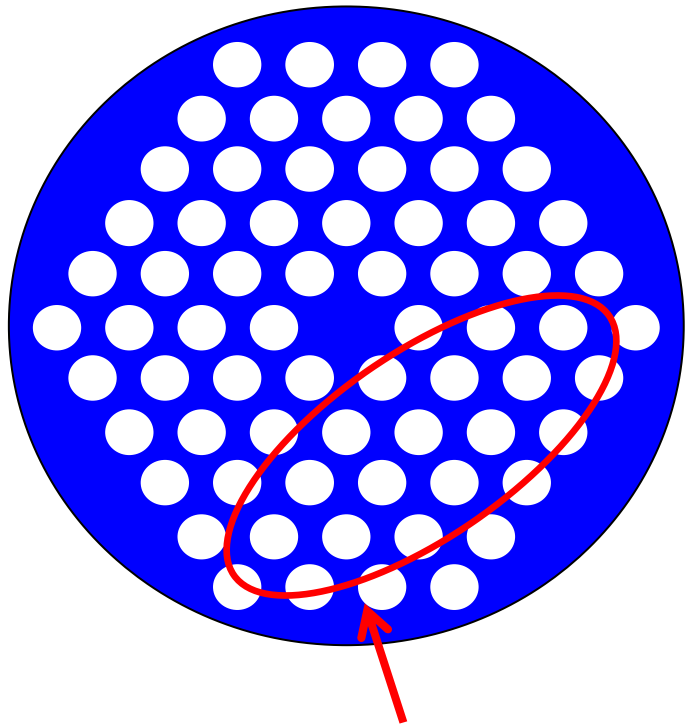
Single-mode analysis

Step-index fiber



$$V = \frac{2\pi}{\lambda} a \sqrt{n_{\mathrm{co}}^2 - n_{\mathrm{cl}}^2}$$

Solid-core PCF



Fundamental space-filling mode

n_{FSM}

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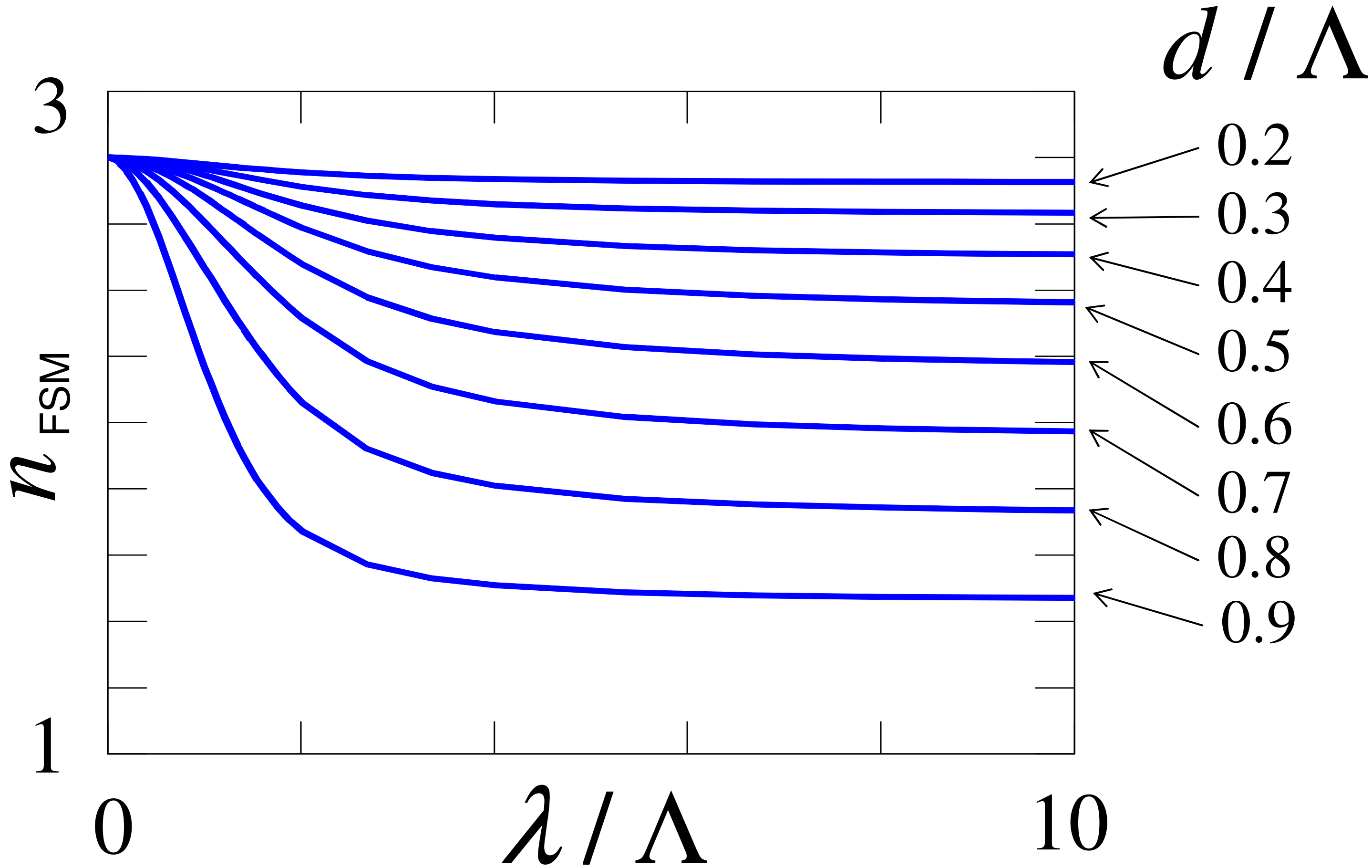
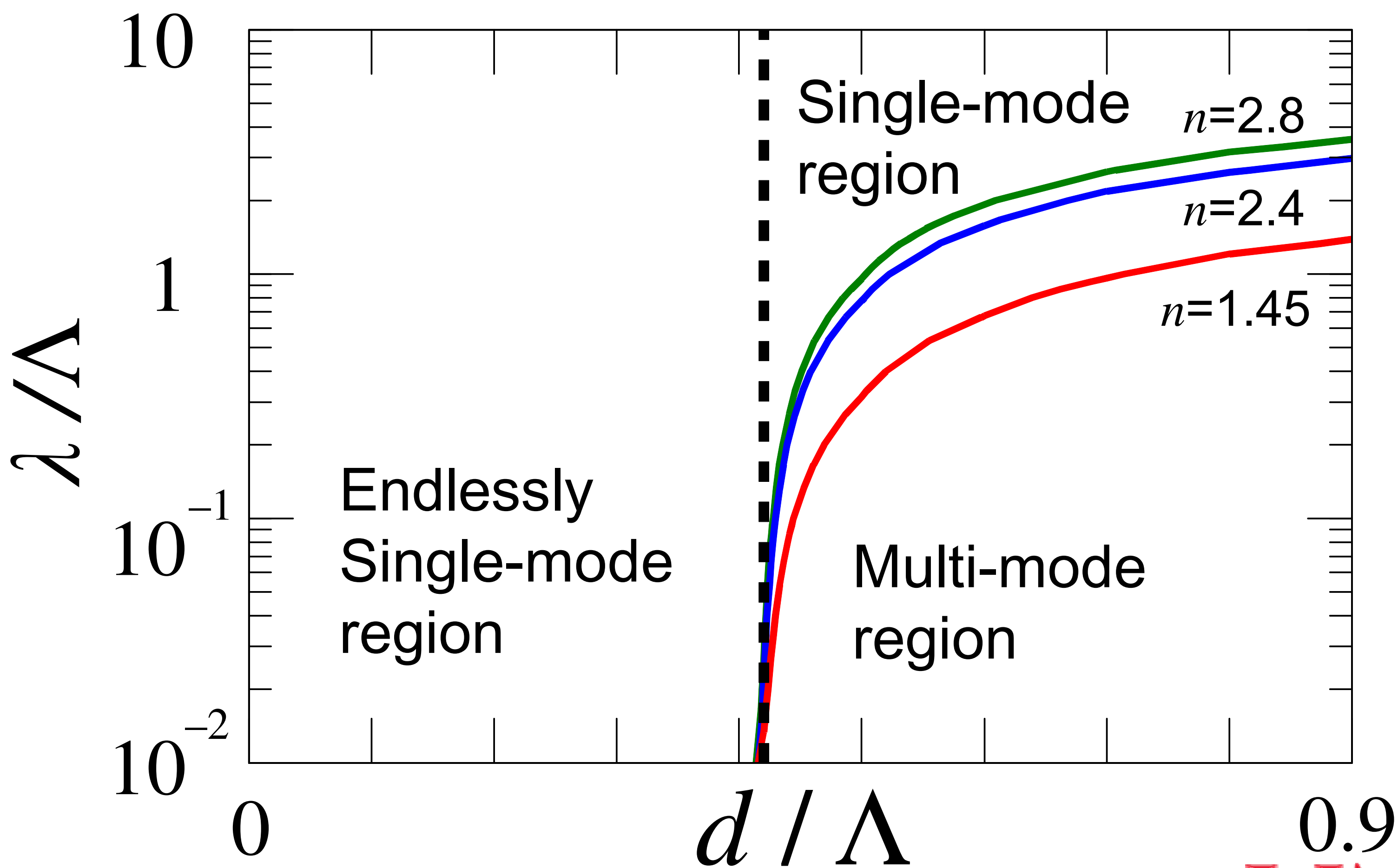
Fundamental space-filling mode



Endlessly single-mode region



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Endlessly single-mode region

What we learned:

When $d/\Lambda = 0.4$, the fiber is single mode

AND

We have the best mode confinement.

We set $d/\Lambda = 0.4$ from this point on.

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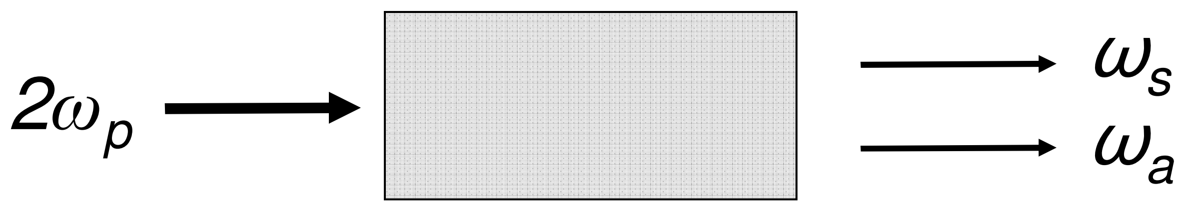
Four-wave mixing (FWM)



Phase-matching condition

$$(n_s\omega_s + n_a\omega_a - 2n_p\omega_p)/c + 2(1-f_R)\gamma P_p = 0$$

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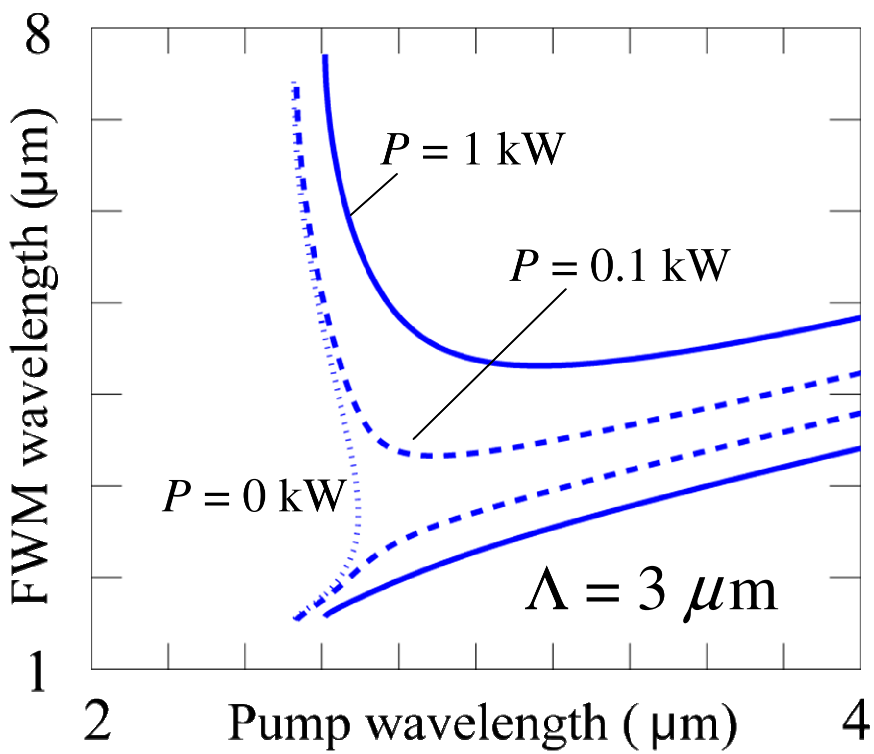
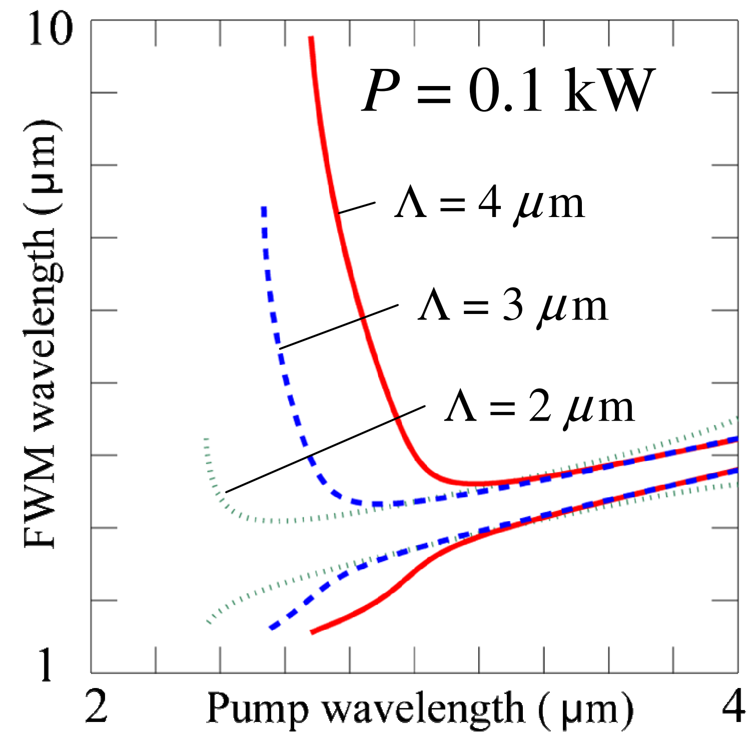
FWM wavelength





At $P = 0.1\ \mathrm{kW}$, $\Lambda = 3\ \mu\mathrm{m}$ gives a large Stokes wavelength

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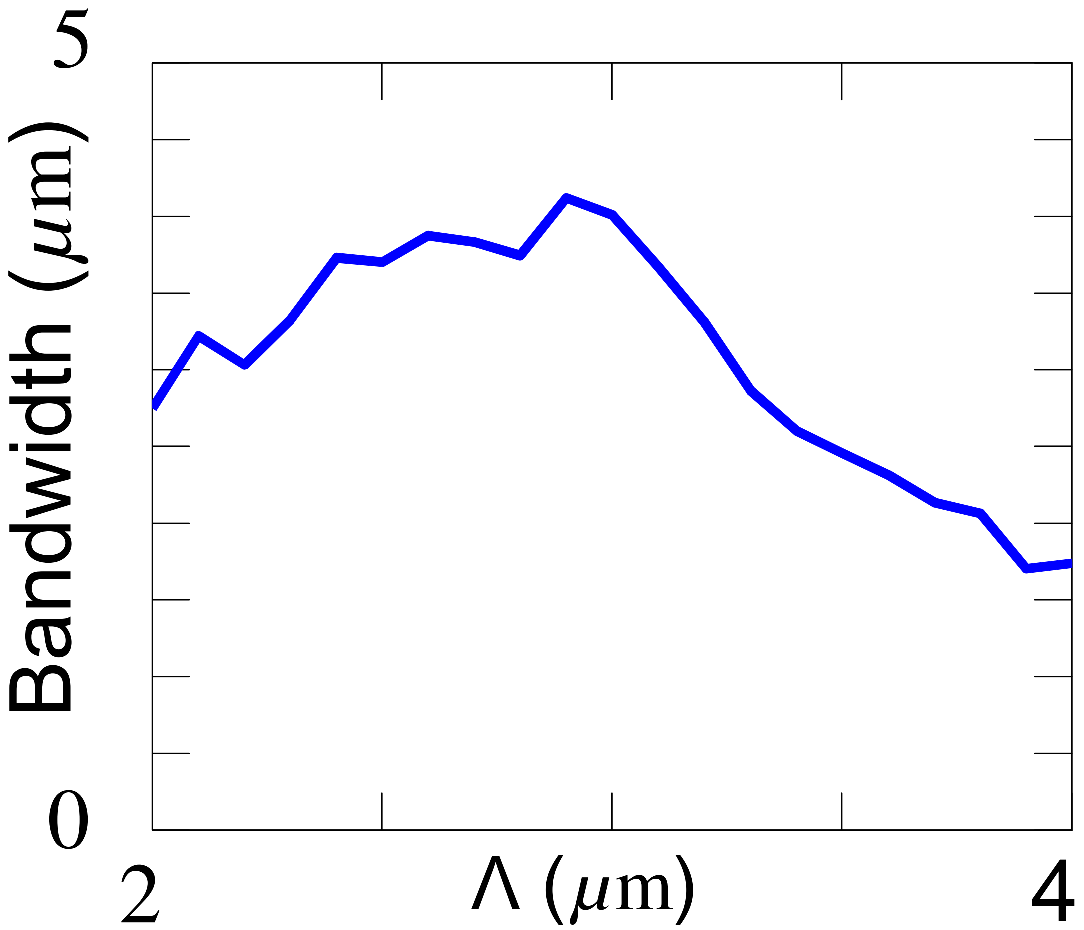
Bandwidth as a function of pitch



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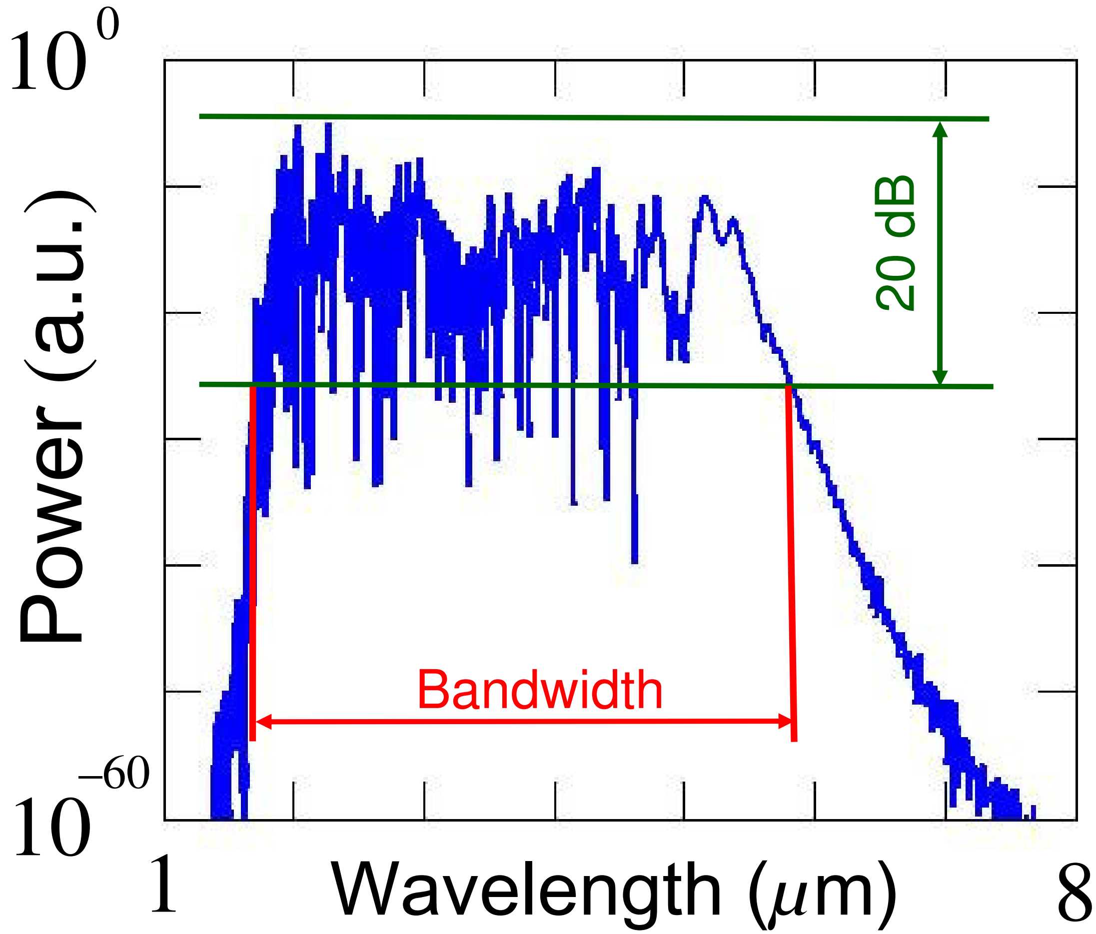
Output spectrum



L = 0.1 m
FWHM = 500 fs
d/Λ= 0.4
Λ = 3 μm

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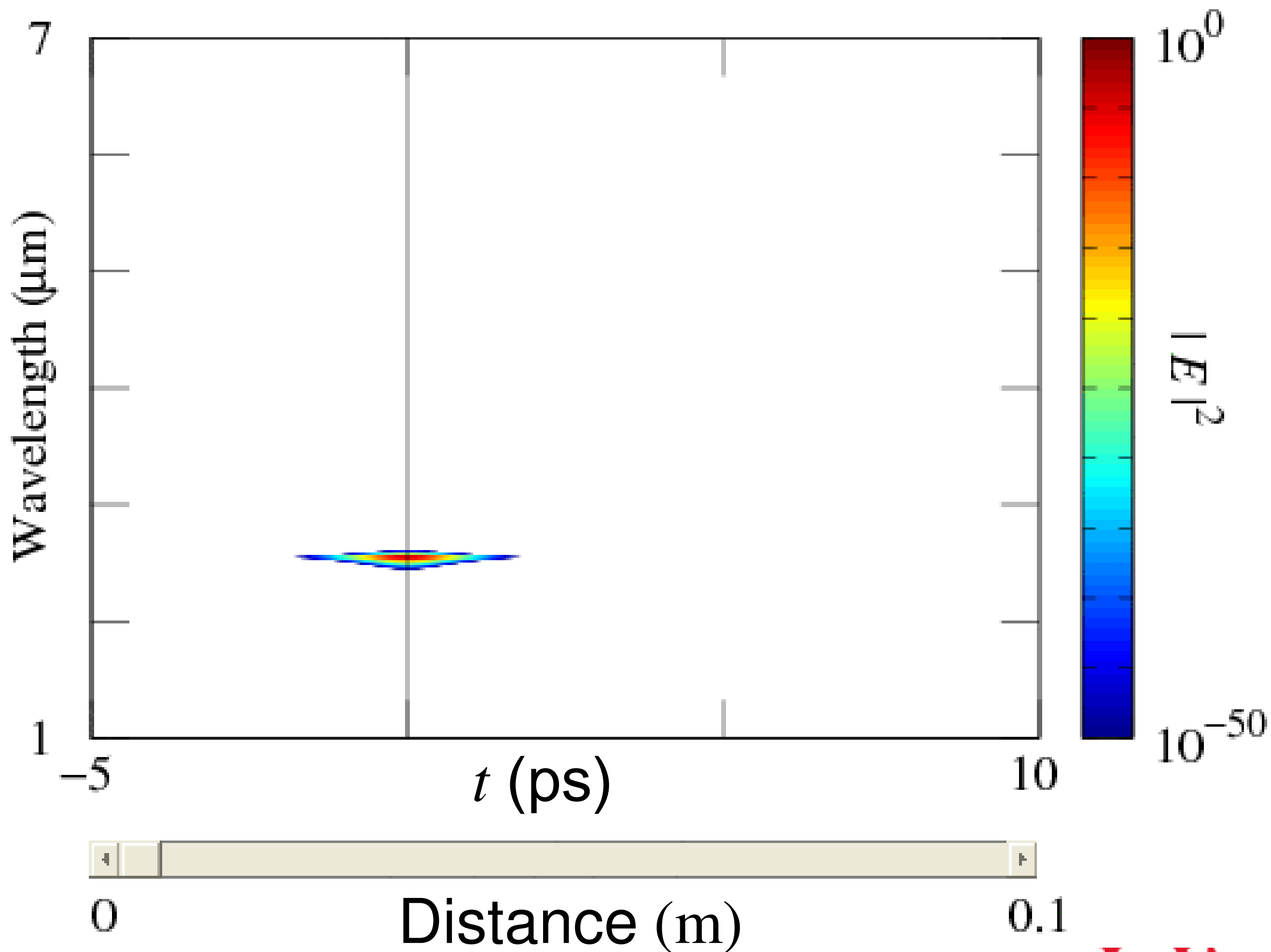
Spectrogram



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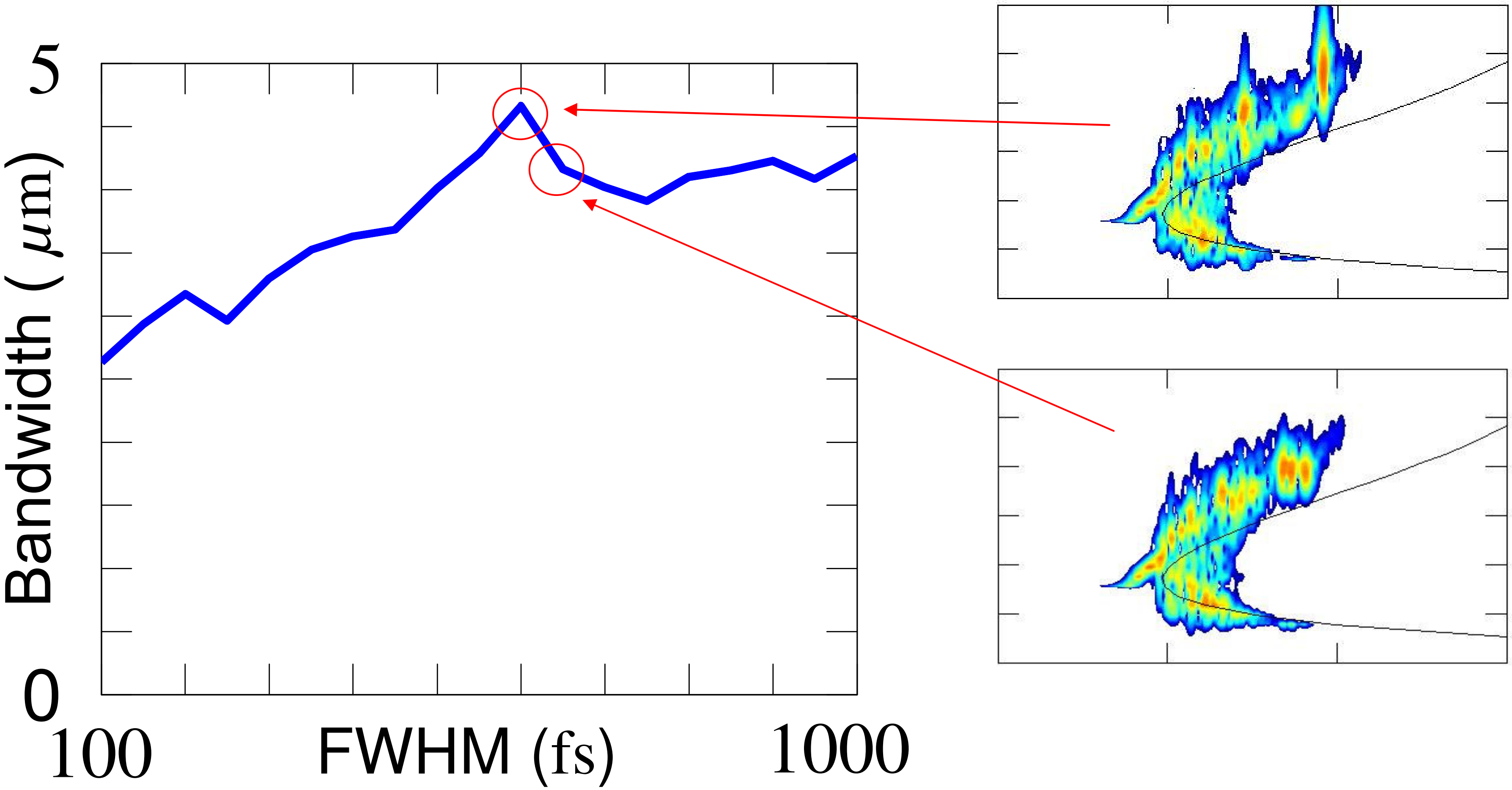
Bandwidth as a function of input pulse width



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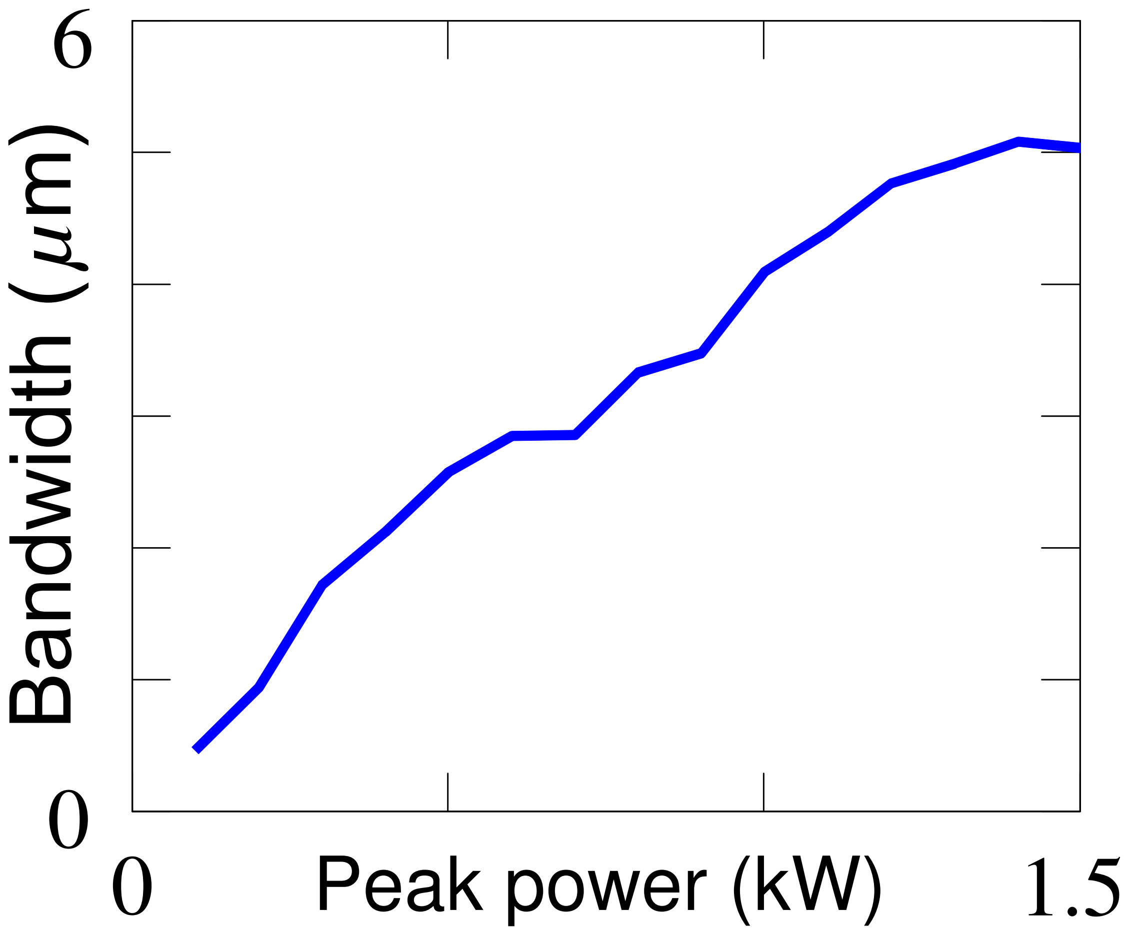
Bandwidth as a function of input peak power



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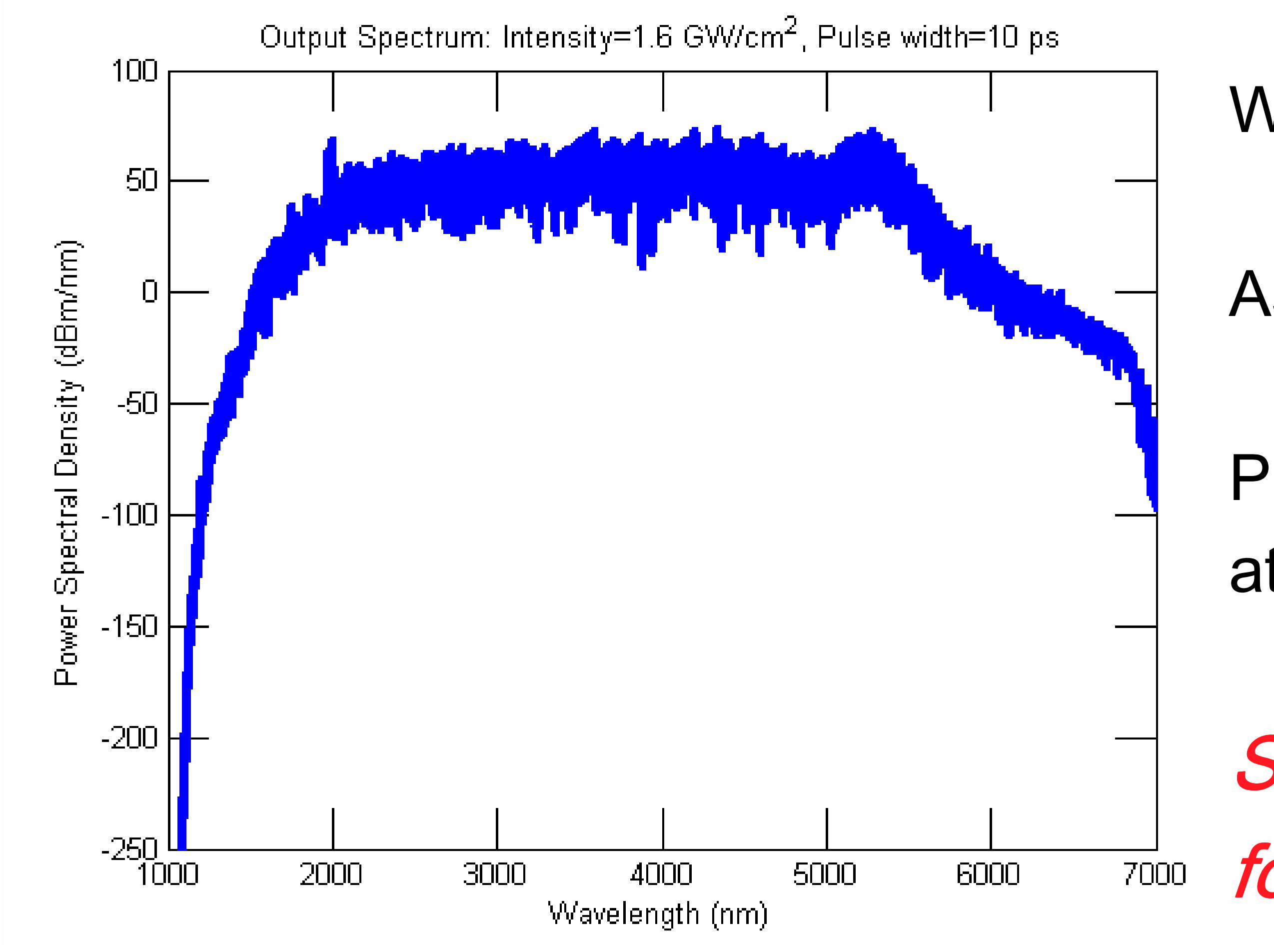
Application of this approach to other fibers



Weiblen, *et al.*

As_2S_3 fiber

Presented
at CLEO 2010

Stay tuned for more!

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Conclusions

- We have developed a design approach that allows us to maximize the supercontinuum bandwidth in chalcogenide fibers

- We showed that a bandwidth of 4 μm can be generated using an As_2Se_3 PCF with d/Λ = 0.4 and Λ = 3 μm at a pump wavelength of 2.5 μm

- This same approach can be applied to a wide variety of chalcogenide fibers.

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Thank you!